Exoplanet Demographics Beyond *Kepler*

Giant Planets detected with Radial Velocity & Young Planets with TESS

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The *Kepler* Mission

- **Mission Goal:** To detect Earth-sized planets in the habitable zone (HZ) of a Sun-like star (SpTy: FGK)
- **Lifetime:** March 2009-May 2013
- **Constellations:** Cygnus, Lyra and Draco
  - Greater concentration of FGK stars

Thompson et al. 2017 using Kepler dr25

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Giant Planets Detected with Radial Velocity

- How different are the *Kepler* and radial velocity (RV) Giant Planet (GP) distributions?
- What is GP distribution across all orbital separations?
- Is there really a break/turnover at larger orbital separations as predicted by planet formation models?
Data: *Kepler* and Radial Velocity (RV)

- **Method:** Transit
- **Measures radius**
- **Close in planets (<480 days)**
- **GP:** $5 - 20 \, R_\oplus$

- **Method:** Radial Velocity (RV)
- **Measures mass (more specifically $m_{\sin i}$)**
- **Wide orbital range (out to 10,000 days)**
- **GP:** $30 - 6000 \, M_\oplus (0.1 - 20 \, M_J)$

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Occurrence Rate Calculations

\[ \eta_{\text{bin}} = \frac{1}{n_*} \sum_{j}^{n_p} \frac{1}{\text{comp}_j} \]

Where \( n_* \) is the number of stars and \( \text{comp}_j \) is the survey completeness evaluated at the radius/\( msini \) and orbital period of each planet in the bin.

Importance of Completeness:

Observed distribution vs. Intrinsic distribution of exoplanets

Fernandes+ 2019; Kyle Pearson
Result 1: RV vs Kepler

- GP occurrence rate increases as a function of orbital period (consistent with previous results).
- RV and Kepler curves are the same within errors
  - RV can be used as an extension of Kepler

Fernandes+ 2019
Result 2: Turnover at the Snowline

A Python code to compare synthetic planet populations to the observed planet populations (Mulders+ 2018, 2019; https://github.com/GijsMulders/epos)

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Past Predictions for Direct Imaging

**Kepler (Kopparapu+ 2018):**
Extrapolated rate (within 20 au): 101%

**RV (Cumming+ 2008):**
Extrapolated rate (10-100 au): 15%
Result 3: Predictions for Direct Imaging

- Extrapolate Broken Power-law instead, using epos
  - Asymmetric: $0.4^{+1.8}_{-0.3}\%$
  - Symmetric: $1.0^{+0.7}_{-0.4}$

- Lower than single power-law extrapolations by orders of magnitude

- Consistent with observed rates (GPIES - Nielsen+ 2019)
Half-way Summary

• What we did:
  • Compared the *Kepler*’s giant planet frequency with that of RV (Mayor+ 2011)

• What we found:
  • The occurrence of *Kepler* and RV as a function of orbital period agree with errors
  • Robust evidence for a break at the snowline (∼2-3 au)
  • Extrapolation of this gives more consistent rates when compared to the observed Direct Imaging rates (∼1%)

Fernandes+ 2019

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Young Planets with TESS

• What does the short-period planet population look like in young clusters?
• How does this young population compare with Kepler's Gyr-old population?
• How can young planets help us refine EtaEarth?
The $\eta_\oplus$ Problem

$\eta_\oplus$: the frequency of Earth-sized planets in the Habitable Zone (0.9 – 2.2 $P_\oplus$; 0.7 – 1.5 $R_\oplus$) of a Sun-like star

$\eta_\oplus$: 36% (epos; Mulders+ 2018)

Pascucci et al. 2019 using Kepler dr25
The Population of Small, Short-period Planets

Possible explanations:

- XUV Photoevaporation (Owen+Wu 2013, 2017)
- Core-powered Mass Loss (Gupta+Schlichting 2019, 2020)
The population of short-period small (<1.8 $R_⊕$) planets maybe contaminated by the stripped cores of once sub-Neptunes and hence is not representative of planets that formed like Earth.

How do we quantify this contamination by the stripped cores of once sub-Neptunes?
With the Transiting Exoplanet Sky Satellite (TESS) mission, we now have the unique opportunity to detect planets around stars in young clusters and associations, providing a sample much closer in time to the primordial short-period planet population.

Detections of young planets with K2+TESS fill the gaps in Kepler’s radius-period plane.
Our Sample of Young Stellar Clusters

- Age: 10 Myr – 1 Gyr
- Distance: < 200 pc

⇒ 8370 stars from 27 young clusters and moving groups

(Gagné et al. 2018 and Gaia DR2 (Babusiaux et al. 2018))
Finding Planet Candidates

pterodactyls
Python Tool for Exoplanets: Really Outstanding Detection and Assessment of Close-in Transits around Young Local Stars

- Extract Light Curves from Full Frame Images using eleanor (Feinstein+ 2019)
- Detrend Light Curves using a penalized spline from Wötan (Hippke+ 2019)
- Search for Planets using TLS (Hippke+Heller 2019)
- Vet exoplanet candidates using triceratops (Giacalone et al. 2020)
- Fit phase-folded light curve using EXOTIC (Zellem et al. 2020)
Detrending Light Curves of Young Stars

Penalized Spline With Knot Optimization Based on Stellar Rotation Rates
Result 1a: Recovery of Known Planets

Cluster: IC 2602
Radius: 7.2 R⊕
Period: 8.3 days

Cluster: THA
Radius: 5 R⊕
Period: 8.2 days

Cluster: IC 2602
Radius: 3.5 R⊕
Period: 2.8 days

Nardiello et al. 2020
Newton et al. 2019
Nardiello et al. 2020
Result 1b: Recovery of Multi-Planet Systems

Cluster: Pisces-Eridani
Radius: 3.6 \( R_\oplus \)
Period: 16.4 days

Cluster: Pisces-Eridani
Radius: 2.6 \( R_\oplus \)
Period: 9.2 days
Result 2: New Detections

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Summary & Future Work

• Many of the short-period Earth-sized planets might be the stripped cores of once sub-Neptunian planets. An extrapolation of this population to the HZ leads to an overestimation of $\eta_\oplus$.

• By measuring the occurrence of yet unstripped short-period sub-Neptunes in young (10-500 Myr) stellar clusters with TESS, we can quantify the contamination of stripped cores in the short-period planet population.

• Our code, pterodactyls, has been optimized to be able to detrend young light curves from TESS FFIs.

• Next steps:
  • Search and vet planet candidates in entire sample
  • Community Follow-up of planet candidates
  • Uniform characterization of stars in young clusters
  • Measure occurrence of young Super Earths and sub-Neptunes
Extra Slides
Kepler’s Impact of ExoEarth Formation

**ExoEarths**

- Form in a gas-poor environment + Atmosphere from outgassing
- Planets can form with a thick hydrogen atmosphere and then lose it (Stripped Cores)
Result 2: Turnover at the Snowline

- CRAN segmented:
  - Can the distribution be fit with one or multiple line segments?
  - Asymmetric
    - $p_{\text{pre-break}} = 0.55^{+0.05}_{-0.05}$
    - $p_{\text{break}} = 1679^{+252}_{-252}$ days
    - $p_{\text{post-break}} = -1.21^{+0.24}_{-0.24}$
  - Symmetric
    - $p_{\text{pre-break}} = -p_2 = 0.57^{+0.09}_{-0.09}$
    - $p_{\text{break}} = 855^{+131}_{-131}$ days
- Log normal (Meyer+ 2018)
  - $p_{\text{break}} = 919^{+105}_{-105}$
Exoplanet Population Observation Simulator (EPOS)

- A Python code to compare synthetic planet populations to the observed planet populations (Mulders+ 2018, 2019)

Applications: Mulders+ 2018, 2019; Kopparapu+2018; Pascucci+2018, 2019; Fernandes+ 2019

- EPOS is available on Github for download: https://github.com/GijsMulders/epos
Exoplanet Population Observation Simulator (EPOS)

- Asymmetric:
  - $p_{pre-break} = 0.70^{+0.30}_{-0.16}$
  - $p_{break} = 2075^{+1154}_{-1202}$ days
  - $p_{post-break} = -1.20^{+0.92}_{-1.26}$
- Symmetric:
  - $p_{pre-break} = -p_{post-break} = 0.65^{+0.20}_{-0.15}$
  - $p_{break} = 1581^{+894}_{-392}$ days